Roadmap for Sustainable Fueling Options in the Maritime Sector

Franz, Sebastian; Campion, Nicolas; Shapiro-Bengtsen, Sara; Münster, Marie

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

ROADMAP FOR SUSTAINABLE FUELING OPTIONS IN THE MARITIME SECTOR

Sebastian Franz[1,*], Nicolas Campion[1], Sara Shapiro-Bengtsen[1], Marie Münster[1]

Affiliation:
[1] *Technical University of Denmark, Energy Economics and System Analysis*
[*] *Corresponding Author: semfr@dtu.dk*

ABSTRACT

The maritime industry is at a crossway. Decarbonization of this sector is an essential part of efforts towards climate change mitigation. Especially the long-distance operations are challenging to decarbonize as electrification is not an option there. Therefore, more and more alternative fuels are being considered to decarbonize the shipping industry. There are options such as PtX, biofuels, blue fuel (ammonia), and electro fuels. However, the choice of the fuel for the future requires an in-depth analysis of different costs, sustainability factors, and biomass availability.

This study answers the question of the least cost fueling option given restrictions in greenhouse gas emissions (GHG) and biomass availability.

We use an open-source linear least-cost optimization model, which utilizes data on biomass availability, shipping demand, vessel expenditure, and fuel price to propose fuel transition roadmaps for the maritime industry. The necessary input data are from the MarE-Fuel project and literature. The future fuel mix will be analyzed, including sustainable maritime fuels, which are essential to decarbonize the maritime industry in the long term. The considered fueling options in this model are electrofuels (methanol and ammonia), biofuels (Refined Pyrolysis Oil, LBG), e-biofuel (Bio-emethanol), blue fuel, lower emission fossil fuels (LNG and VLSFO), and classical fossil fuels (HFO). The potential of these new fuels will be critically assessed by including the GHG emissions of the production process of these fuels. This work aims to identify the main issues the industry is facing at present up until 2050 and provides an outlook on challenges and opportunities towards climate mitigation that the maritime industry might be developing in the future.

We find a diversified picture of a decarbonized maritime future. The future fuel mix is expected to be highly dependent on advancing technologies, ramping up fuel-production facilities, biomass availability, and safety advancements. In an ambitious GHG-emission reduction scenario with high biomass availability, one can see a gap between expected fuel demand and feasible fuel supply given the GHG-emission reduction constraints already from 2028 onwards. In a low biomass availability case, this feasibility gap is even more significant. Given the efforts towards NetZero by 2050, this presents enormous challenges for the decarbonization of the maritime industry at present and for the following years to come.

KEY WORDS

Decarbonization, Energy Economics, Maritime Industry, Market-based Measures, Net-Zero-by-2050

INTRODUCTION

The maritime industry is at a crossway. Decarbonization of this sector is an essential part of efforts towards climate change mitigation. Especially the long-distance operations are challenging to decarbonize as electrification is not an option there. Therefore, more and more alternative fuels are being considered to decarbonize the shipping industry. There are options such as Power-to-X (PtX), biofuels, blue fuel (ammonia), and electro fuels(ammonia and methanol). However, the choice of the fuel for the future requires an in-depth analysis of different costs, sustainability factors, and biomass availability. So far, the use of Low-Carbon-Fuels (LCFs) is minimal due to its expensive production cost. Thus, there must be some Market-based measures (MBM) in place that incentivize the use and expansion of LCFs to bring international shipping on the emission reduction pathway, in line with 1.5 ºC (no or low Overshoot (OS)) scenario. The question of the transformational potential of MBMs remains unanswered, as the overall challenges towards climate mitigation in relation to all emissions along the supply chain are not completely clear yet.

Therefore, in this study, we show the challenges towards climate mitigation to get onto an emission reduction pathway in line with 1.5 ºC (Huppmann et al. 2019) (no or low OS). We apply the open-source least-cost optimization model, SEAMAPS, to calculate the future fueling mix in the maritime industry under certain constraints. Our analysis is based on well-to-wake (WTW) emissions, including emissions from the consumption of electricity from the grid and upstream emissions from the construction of plants. In addition, assumptions were made about the speed of ramping up of production facilities.

The novelty of this modeling approach lies in the lifecycle assessment (LCA) perspective and the bottom-up modeling of LCFs production in combination with feasibility constraints in a least-cost optimization framework. Thus, the model can capture the main dynamics between fossil fuels and LCFs to reveal challenges towards climate mitigation in the maritime industry.

METHODS

The SEAPMAPS model used in this study is an open-source optimization model available under: https://github.com/SebastianFra/SEAMAPS

It uses input data previously derived in the MarE-Fuel project (Franz et al. 2021; Campion et al. 2021; Nami et al. 2021; Copenhagen Economics 2021; Sørensen and Laursen 2021). The relevant boundary conditions, assumptions, variables, and parameters are shown in Figure 1. Once all the required input data has been derived and put into a suitable form, the SEAMAPS starts the optimization process. A cost optimization function is used as the objective function.

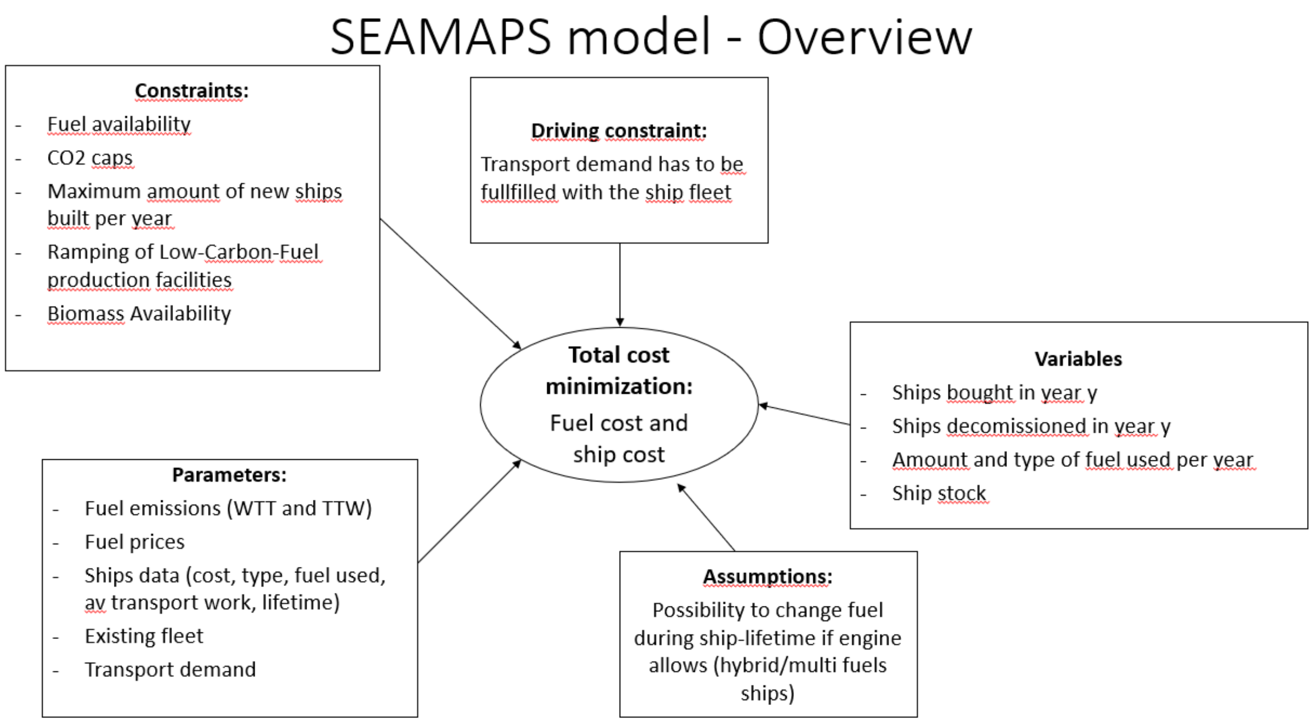

Figure 1: Overview of the Modeling Environment of SEAMAPS

The overall objective is to find the most cost-effective fueling options for the maritime industry. To achieve this, the objective function, which is a cost function, is minimized. The components of the objective function can be divided into two main parts. One part concerns all costs related to the fleet itself, including the investment costs for new vessels and the operation and maintenance costs for the entire fleet. To avoid decommissioning the existing fleet at zero cost, taking an existing vessel out of service before the end of its service life costs half of the original investment. The second cost is limited to fuel costs. The consumption of each vessel in the fleet is multiplied by the fuel cost (including any fuel taxes). The objective function looks as follows:

$$min_{x,q,z,d^{EF}} \sum_{s,y} SI_s * NewBuildShip_{s,y} + SOM_s * ShipStock_{s,y} + SI_s * Decom_{val} * Decomissioned_{s,y}^{EF} + \sum_{s,f,y} FuelUsed_{f,s,y} * (FC_{f,y} + FT_{f,y}) \quad [1]$$

Where SI_s is the investment expenditure for a new build (average) vessel of type s, SOM_s is the operation and maintenance cost for vessel of type s, $Decom_{val}$ is the decommission value factor for discarding an existing ship (equal to 0.5), $Decomissioned_{s,y}^{EF}$ is the amount of decommissioned ships in y, $FC_{f,y}$ is the fuel cost per fuel type and year, $FT_{f,y}$ is the fuel tax added on top of fuel cost (fuel tax is zero in the base case). $NewBuildShip_{s,y}$ is a variable representing the number of new ships of type s bought in year y. $ShipStock_{s,y}$ is a variable representing the total ship stock of ship of type s at year y (variable). $FuelUsed_{f,s,y}$ is a variable representing the amount of fuel bought per fuel type, ship type and year.

Transport demand

This constraint limits the annual supply in the model scheduled to the IMO exogenous demand forecasts(IMO 2021). This ensures that supply and demand match and that there is no excess demand or supply in the model that could bias the results. It is important to note that IMO demand has a strong influence on the future fuel mix results. This variable may need to be replaced with endogenous demand projections to create a more inherent modeling process. For more details, see (Franz et al. 2021).

Ship stock

This constraint ensures the management of the entire fleet(IMO 2021) used in the model for the ship stock. It states that the vessel stock (number of vessels in the world fleet) is equal to the vessel stock in the previous year plus the newly purchased vessels in the current year minus the "retired vessels" in the current year whose service life has expired minus the decommissioned vessels in the current year. Year 1 vessel inventory includes the existing fleet. For more details, see (Franz et al. 2021).

Ship capacity production

The amount of bought ships of type s in year y cannot exceed the industry ship production capacity(Sørensen and Laursen 2021). The production capacity of ship s in year y is 0 when the engine is not available commercially yet. For more details, see (Franz et al. 2021).

Fuel consumption

The amount of fuel used by ships of type s in year y must be enough to satisfy the transport demand(IMO 2021). The transport demand of the fleet of the ship of type s is equal to the ship stock of that type (the number of ships of type s in the fleet) multiplied by the average transport work. The fuel consumption is calculated using the specific fuel consumption per fuel type and ship. Any fuel can be used to satisfy the demand, meaning that more than one fuel type can be used in the same year if the engine is a dual/multi-fuel engine. For more details, see (Franz et al. 2021).

Fuel availability

For all fuels and all years, the amount of fuel used for the whole shipping fleet cannot exceed the fuel available. This fuel availability is highly dependent on biomass availability for biomass-based fuels. In this study, we show a high and low biomass availability scenario. For more details, see (Franz et al. 2021).

CO2e emissions cap

With this constraint, a global CO_2 emissions cap have to be respected every year. To make the model able to solve, this constraint can be broken at a very high cost. In this study, we used Well-To-Wake(Comer and Osipova 2021) (WTW) fuel emissions including emissions related to electricity purchased from the grid and to building infrastructure and plants. The emissions associated with purchasing electricity from the grid follows the IEA Net Zero in 2050 scenario. As an initial starting value for the global cap, we used data from(Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping 2021). For more details, see (Franz et al. 2021)

Ramping of Production Facilities

With this constraint, the uptake of LCFs is limited. This refers to both yearly uptakes of specific fuels and the global availability of LCFs. In our baseline scenario, we used data from (Energy Agency 2021), say LCF can serve only 81% of global maritime demand in 2050.

RESULTS

Our results show significant feasibility problems with fulfilling our exogenous SSP1-type(van Vuuren et al. 2011; Riahi et al. 2017) demand with the existing fueling options and the availability constraint regarding LCFs. In Figure 2, we can see the future maritime fuel supply mix given the above-described constraints for a high and low biomass availability scenario (for more details, see(Franz et al. 2021)) with a grid-connected electro-fuel production setup (with own production from wind and solar power and the possibility to also use electricity from the grid (around 20% on average)). In the short term, one can see that the global fleet will be fueled by fossil fuels such as VLSFO/HFOsc, LNG, and MDO. From 2030 onwards, we see LCFs such as NH3-blue, NH3-green, Refined-Pyrolysis Oil, and MeOH-ebio coming into the fuel mix. This is due to the strict global GHG emission cap needed to be in line with an emission reduction goal of a 1.5 ºC (no or low OS) scenario.

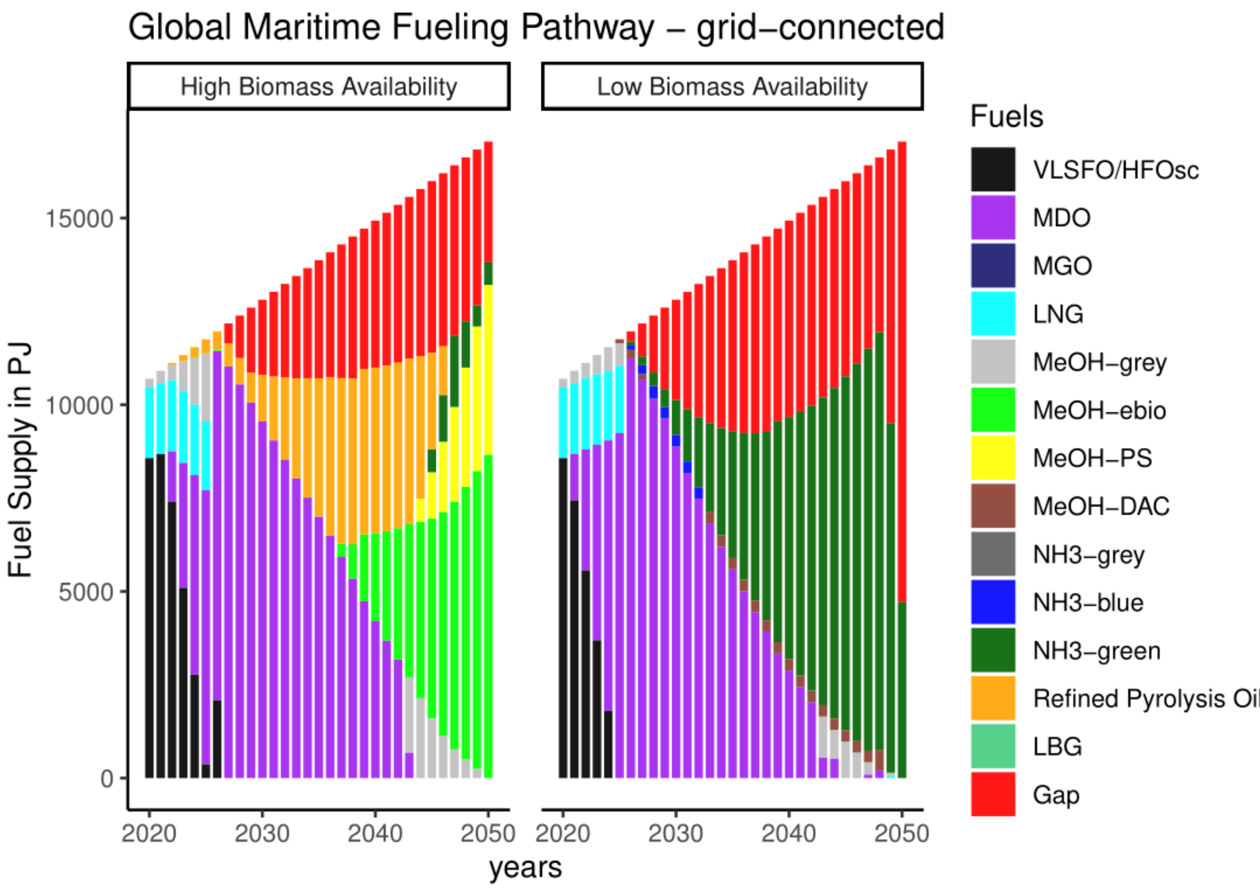

Figure 2: Global Future Maritime Fuel Mix -High Biomass Availability & Low Biomass Availability

Unfortunately, the available LCFs are not enough to fulfill the exogenous demand with the existing fueling options. That is why the model chooses the red fictive fuel "Gap" in both biomass availability scenarios. This "Gap" fuel is characterized by zero-emission and extremely high costs and thus illustrates the only option to fulfill the exogenous demand level constraint at an extremely high cost.

The main difference between the high and low biomass availability cases is the type of LCFs used. In the low biomass availability case, the model uses green ammonia as the primary fuel for the maritime industry. However, in the high biomass availability case, the model uses both Refined-Pyrolysis Oil and MeOH-ebio and methanol using point source biogenic CO_2 (MeOH-PS) as the primary future fuels. Furthermore, the "Gap" fuel usage is higher in the Low Biomass Availability case, illustrating more significant challenges towards climate mitigation in the Low Biomass Availability case (apart from challenges regarding the use of NH3-green due to toxicity and operational problems(Duijm, Markert, and Paulsen 2005)).

When looking at Emission profiles in Figure 2, one can see the transformational potential needed to bring the maritime sector onto emission reduction pathway in line with a 1.5 ºC (no or low OS) scenario.

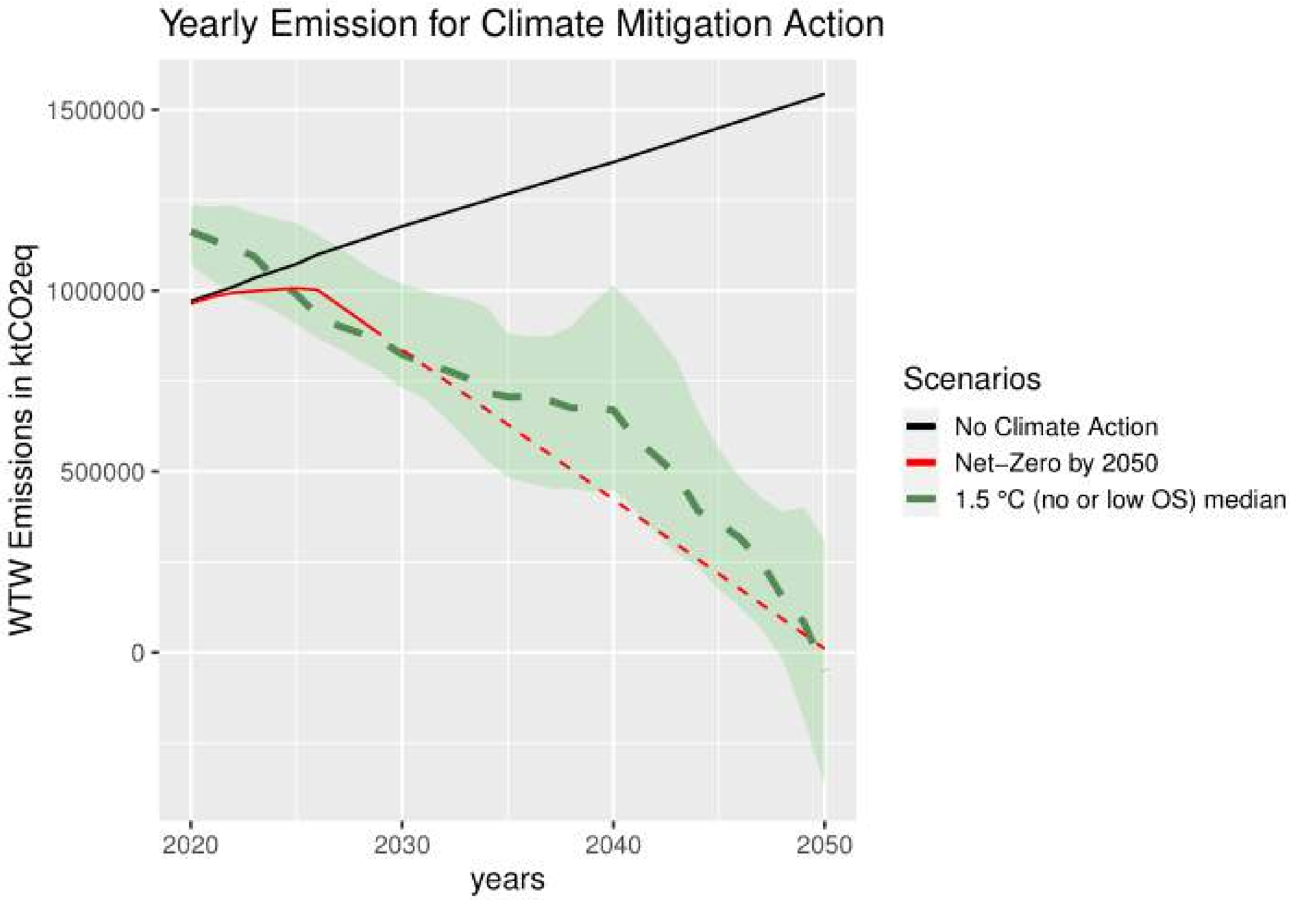

Figure 3: Emission profiles of different climate action efforts

In Figure 3, we show the theoretical WTW + infrastructure emission profiles for a necessary decarbonization pathway to be in line with 1.5 ºC (no or low OS) as well as for a no climate action at all scenario ("No Climate Action"). Furthermore, we show the median, 25th, and 75th quantile of all 1.5 ºC (no or low OS) scenarios provided by (Huppmann et al. 2019) and scaled down to the maritime sector with the WTW emissions from (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping 2021). One can see that in theory, we can not be within an emission reduction pathway of 1.5 ºC (no or low OS). As the red dashed line indicates, this is not possible due to feasibility problems(see Figure 1 – usage of fictive "Gap" fuel.). In other words: Already from 2028 onwards, the by then-existing fueling options are not sufficient to fulfill the exogenous (SSP1-type(van Vuuren et al. 2011; Riahi et al. 2017)) demand and remain on a 1.5 ºC (no or low OS) emission profile if the e-fuels are not using electricity with zero emissions. This illustrates the enormous transformational potential needed to overcome this feasibility gap in the years to come to decarbonize the maritime industry from an entire lifecycle perspective effectively. IMOs 50% reductions target by 2050 (International Maritime Organization 2018) seems more realistic but not sufficient to stay within Paris Agreement pledges. Thus there is an urgent need to formulate more ambitious reduction targets within the maritime industry to fulfill Paris Agreement pledges.

DISCUSSION & CONCLUSION

As our results show, it is impossible to meet the requirements necessary to lead the maritime sector onto an emission reduction pathway in line with a 1.5 ºC (no or low OS) scenario. This is mainly because of the constraint regarding the availability of LCFs in the future. Therefore, it is essential to significantly lower challenges towards climate mitigation within the maritime industry to massively invest in new fuel production facilities and renewable electricity. This massive ramping of LCFs production would contribute to a cleaner naval sector.

Another technological challenge arises when looking at the availability of biomass. For a low biomass availability case and thus a high usage of green ammonia (see Figure 2), there are safety issues(Duijm, Markert, and Paulsen 2005; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping 2021) regarding toxicity for humans and marine life and operational feasibility challenges, which have to be solved before usage. On the other hand, a high biomass availability case seems unlikely since other industries (e.g., aviation, petrochemicals) also demand massive ammounts of biomass.

Furthermore, technological progress alone may not be the only option to lower mitigation challenges. Reducing fuel consumption in general, be it with a change in consumers behavior, to ultimately consume less, or the ban of fuel-intensive logistic routines (e.g., "SFTW" – "Steam Fast then Wait" concept") could save a significant amount of GHG emissions(Zografakis 2021; Jia et al. 2017) and thus make it easier for technological progress to lead the maritime sector onto emission reduction pathway in line with a 1.5 ºC (no or low OS) scenario.

Future research could investigate different Market-Based Measures (MBMs) to incentivize the usage and expansion of LCFs effectively. An overview and comparison of stylized MBM-scenarios following different basic MBM-designs(Psaraftis, Zis, and Lagouvardou 2021) and their impact and transformational potential for a decarbonized maritime sector could be of great value. This analysis would enable us to analyze more realistic scenarios, and help us to build uniform expectations across all stakeholders towards necessary transformation (e.g., needed carbon price or ban of fossil fuels) for the industry to be not just theoretically but effectively decarbonized.

Finally, our analysis shows there are enormous challenges towards climate mitigation within the maritime industry. With technological solutions alone, we find that a decarbonized international shipping industry faces feasibility problems already from 2028 onwards. Therefore, lowering the overall challenges towards climate mitigation by reducing fuel consumption, either by cutting demand or improving efficiencies, is essential for the following years to come. With considerable efforts in technology, policy, and contractual design, a decarbonized maritime industry by 2050 could become a reality.

ACKNOWLEDGEMENTS

This paper is published as part of the MarE-Fuel project funded by the Danish Maritime Fund and the Lauritzen Fund as well as the DeMAR SOSD project funded by the Danish Orient Fund. We thank the partners of the projects for their cooperation and inspiration.

Campion, Nicolas, Martijn Backer, Phil Swisher, and Marie Münster. 2021. "MarE-Fuel: LCOE and Optimal Electricity Supply Strategies for P2X Plants."
Comer, Brian, and Liudmila Osipova. 2021. "Accounting for Well-to-Wake Carbon Dioxide Equivalent Emissions in Maritime Transportation Climate Policies."
Copenhagen Economics. 2021. "CO2-Taxes, Fuel Prices and Learning Rates."
Duijm, Nijs Jan, Frank Markert, and ette Lundtang Paulsen. 2005. "Safety Assessment of Ammonia as a Transport Fuel."
Energy Agency, International. 2021. "World Energy Outlook 2021." www.iea.org/weo.
Franz, Sebastian, Nicolas Campion, Sara Shapiro-Bengtsen, Martijn Backer, and Marie Münster. 2021. "MarE-Fuel: ROADMAP for Sustainable Maritime Fuels."
Huppmann, Daniel, Elmar Kriegler, Volker Krey, Riahi Keywan, Rogelj Joeri, Katherine Calvin, Florian Humpenoeder, et al. 2019. "IAMC 1.5°C Scenario Explorer and Data Hosted by IIASA." August 8, 2019.
IMO. 2021. "Fourth IMO GHG Study 2020 Full Report."
International Maritime Organization. 2018. "Initial IMO GHG Strategy." 2018.
Jia, Haiying, Roar Adland, Vishnu Prakash, and Tristan Smith. 2017. "Energy Efficiency with the Application of Virtual Arrival Policy." *Transportation Research Part D: Transport and Environment* 54 (July). https://doi.org/10.1016/j.trd.2017.04.037.
Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. 2021. "We Show the World It Is Possibe - Industry Transiton Strategy."
Nami, Hossein, Giacomo Butera, Nicolas Campion, Henrik Lund Frandsen, and Peter Vang Hendriksen. 2021. "MarE-Fuel: Energy Efficiencies in Synthesising Green Fuels and Their Expected Cost."
Psaraftis, Harilaos N., Thalis Zis, and Sotiria Lagouvardou. 2021. "A Comparative Evaluation of Market Based Measures for Shipping Decarbonization." *Maritime Transport Research* 2: 100019. https://doi.org/10.1016/j.martra.2021.100019.
Riahi, Keywan, Detlef P. van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O'Neill, Shinichiro Fujimori, Nico Bauer, et al. 2017. "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview." *Global Environmental Change* 42 (January): 153–68. https://doi.org/10.1016/j.gloenvcha.2016.05.009.
Sørensen, Thorben Anker, and Rene Laursen. 2021. "Total Cost of Ownership (TCO) - Sustainable Marine Fuels."
Vuuren, Detlef P van, Elke Stehfest, Michel G J den Elzen, Tom Kram, Jasper van Vliet, Sebastiaan Deetman, Morna Isaac, et al. 2011. "RCP2. 6: Exploring the Possibility to Keep Global Mean Temperature Increase below 2 C." *Climatic Change* 109 (1): 95–116.
Zografakis, Haris. 2021. "The Third Pillar: A Contractual Architecture for Maritime Decarbonisation."